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MATERIALS APPROACHES TO SHIP SILENCING

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A survey of high-damping materials shows that two basic alloy systems, Ni-Ti and Cu-Mn, currently have been developed to the point of commercial availability and general engineering attractiveness. Alloys from both systems have the potential of wide application for noise/vibration reduction. The damping capacity of these "quiet metals" is so unusually high that new methods of design integration for noise reduction should be developed. The NPS research program in FY 74 has concentrated on the characterization of metallurgical factors (such as stress, deformation, and aging) affecting damping capacity

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in Cu-Mn-base alloys, and has studied the control of damping properties through thermomechanical processing. The program has also evaluated the effectiveness of various techniques to measure damping properties in high-damping alloys; torsion pendulum, resonant bar, and ultrasonic pulse-echo methods have been examined.

MATERIALS APPROACHES TO SHIP SILENCING

by

J. Perkins, G. R. Edwards, and N. Hills

FY 1974 Report

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I. Introduction

"Quiet", in the form of noise and vibration reduction, is highly desirable in both submarines and surface ships. This applies to both "hare" and "hound" roles in anti-submarine warfare (ASW) and to the general operational desirability of low noise levels. Briefly, the situation can be summarized as follows: A submarine, to remain undetected by passive listening sonars, must be quieter than the background ambient noise in which it exists; and to take advantage of itself as a superior sonar platform, it must not produce noise or vibration that would detract from its capability to discriminate a contact from the background noise. In order to accommodate both these requirements, it is desirable to minimize transmission of noise and vibration generated by submarine machinery (i) from the hull to the sea, and (ii) from the machinery to the on-board sonar.

Practical approaches to noise/vibration control may involve one or both of two basic schemes: (i) isolation, i.e. prevention of energy transmission between the sources (machinery) and the surfaces which can radiate the energy; and (ii) dissipation or attenuation of the energy somewhere in the structure. To date, the former scheme (isolation) has received by far the most widespread application, as in the form of resilient mounts for shipboard machinery. There is extensive use of resilient mounts throughout submarines. However, isolation is only one possible approach, and one which may be comparatively naive. Resilient mounts also can consume considerable valuable space and add weight.

A more sophisticated approach to reduction of energy transmission would involve design of machinery with vibration control in mind, to

effectively dissipate energy through design and the use of energy-absorbing materials as components. To date, only two ship design components have been emphasized, these being machinery foundations and propellers. There are many individual components that may yet be usefully treated for vibration control, including gears, pumps, valves, piping, and bearings, not to mention analysis of component interaction through acoustic signature of machinery systems. In the simplercase of individual component design, materials considerations can be highly significant, and have been the primary concern of the NPS investigative program during FY 74.

II. NPS Investigative Program

The NPS research program has concentrated initially on potential materials solutions to ship silencing problems. The following sections (II.A., II.B., II.C.) describe the evolution which has led to the on-going program. Section II.A. generally describes the state-of-the-art in high-damping materials. Section II.B. summarizes in detail the features of "quiet metals" of particular interest, the Cu-Mn-base alloys; this description has resulted from a detailed survey and digestion of existing literature. The ideas gained from this process led directly to the investigative plan outlined in Section II.C. This program is, of course, still in progress. Progress and results to date are summarized later in this report (Sections III and IV).

II.A. Potential Materials Solutions to Noise-Vibration Problems

It is clear that materials selection with damping properties in mind, together with design integration of individual components, can potentially yield significant reductions in noise/vibration levels. The general damping (energy dissipation) properties of available materials are summarized in Figure 1 as a rough guide. This table must be regarded as only approximate because there is commonly a dependence of damping on stress, temperature, and thermomechanical history of the material. The most commonly used index of damping is the "specific damping capacity", defined as the percentage of strain energy dissipated during a stress cycle, measured at a stress level one tenth the tensile yield strength.

In the area of high-damping materials (SDC > 35), two alloys groups have particular attractiveness as engineering materials for ship silencing applications; namely (i) the Cu-Mn-base alloys, and (ii) Nitinols (Ni-Ti-base alloys). In both of these alloy groups, the exceptionally

high damping capacity can be related to the action of unique submicroscopic structural features in stress-induced lattice transformations (i.e. under cyclic elastic loads, energy absorption takes place by the oscillation of certain unique fine-scale features). The uniqueness of this mechanism to these two groups of alloys (among those listed in Figure 1) can be fundamentally related to the details of the crystallography and morphology of the martensitic transformation products in these alloys. Most other alloys do not exhibit such high damping because they either (i) do not exhibit martensitic transformation, or (ii) the crystallographic details of the martensitic transformation are not appropriate. However, it is considered (by the present investigators) that the energy dissipation features and mechanisms typified by Cu-Mn and Ni-Ti alloys are also common to several as-yet-undeveloped alloy systems (not listed in Figure 1), such as certain martensitic Cu-Sn, Cu-Al, Ni-Al, and Fe-Ni alloys, among others. Alloy development in these systems would very likely yield other practical high-damping engineering materials. This prognosis is based on an appreciation of common crystallographic features and lattice transformation features (such as shape-memory effects) in all of these alloys[(1)]. The present NPS investigative program has been initially limited to studies in the Cu-Mn system, but may later be logically extended into other systems.

II.B. Analysis of Physical Metallurgy of Cu-Mn "Quiet Metal" Alloys

As a first step to investigating the potential of high-damping "quiet metal" alloys, a detailed survey and analysis of previous metallurgical studies of Cu-Mn-base alloys was conducted. The purpose of this effort was to delineate as best as possible the physical metallurgy, transformation behavior, and deformation response of the

Cu-Mn alloys (topics about which there has been considerable confusion and ambiguity in the literature). This knowledge would then permit intelligent design of the subsequent experimental metallurgical development program for these alloys.

The Cu-Mn binary phase diagram is shown in Figure 2. High damping is associated with alloys of greater than about 20% Mn; practical alloys range from about 70 Cu-30 Mn to 30 Cu-70 Mn. These alloys must be subjected to four heat-treatment steps in order to be properly "conditioned" for optimum damping properties: (1) solution treatment in the $\alpha[\gamma_{Mn}]$ single phase region; (2) quench to retain the high temperature phase; (3) aging treatment (e.g. approximately 2 hours @ 400°C) in the two-phase ($\alpha + \alpha_{Mn}$) region; (4) quench to room temperature (during which martensitic transformation of the matrix occurs). Underaging or overaging during the third step will result in inferior damping properties. The sequence of events and resulting structures during these steps is summarized in Figure 3.

In summary, the optimum damping condition is obtained by a diffusional (conditioning) reaction (Step 3 in Figure 3) followed by a diffusionless transformation (Step 4 in Figure 3). The purpose of the aging treatment (Step 3) is to condition the γ_{Mn} matrix phase to a Mn-enrichment level sufficient to allow martensitic transformation (Step 4) above room temperature (note superimposed in Figure 2 the trend of T_N and M_s with γ-phase composition). It is actually the resulting room temperature martensitic microstructure which allows high energy absorption through its particular crystallographic and morphological features.

A further area of interest prior to initiating experimental work was the existing literature concerning effects of deformation and stress (at any stage prior to and/or during the heat treatments outlined above) on

the resulting damping properties. In fact, the central aim of the NPS investigative program was envisioned initially to be metallurgical control of damping properties through thermomechanical processing (i.e. manipulation of temperature-deformation history). To this end, the existing relevant literature was surveyed and analyzed. Two general effects were of interest (i)the effect of elastic stresses, and (ii) the effect of plastic deformation.

Elastic stress of martensite structures

It has been widely observed that specific damping capacity (SDC) of Cu-Mn alloys increases with the level of the elastic stress applied to the martensitic structure during damping measurement; this applies to static stresses or the amplitude of the cyclic stress (2,3).

Plastic deformation of martensite structures

SDC is decreased by plastic deformation of aged and quenched (martensitic) structures [4]. "Retransformation" (reheat above A_f, e.g. to about 250°C for five minutes) restores original levels of SDC only if the percentage deformation was less than about 10%[4]. Specimens deformed 1-2% after aging and quenching, then "retransformed", exhibit an increase in SDC[4]. The general explanation for this behavior is that dislocations produced by deformation of the martensitic microstructure generally interfere with the submicroscopic twin boundary oscillatory motion necessary for energy absorption. A "retransformation" treatment causes the martensite to revert and redistribute on quenching according to the dislocation arrangement (still persisting above A_f), i.e. the dislocations will likely then be arranged so as to interfere less with the damping mechanism, unless the dislocation density is so high that they cannot help but interfere. The details of any dislocation-martensite interactions is not clearly known; also not completely explained is the observed increase in SDC at slight deformations (followed by retransformation[4]).

Goodwin[3] has reported that very low plastic deformations of martensite (< 0.1%) without retransformation also increases SDC, while higher deformations reduce SDC. INCRA research[5] indicates that > 0.5% deformation decreases SDC in a modified Cu-Mn alloy ("Incramute" commercial alloy).

In general, in a polycrystalline martensitic microstructure, plastic deformation can occur by (i) glide; (ii) twinning-detwinning; (iii) re-orientation of martensitic plates; (iv) stress-induced phase transformation. In a low-symmetry martensite, only a few orientation variants of (i) or (ii) may be available. In some martensites apparent plastic deformation by modes (ii), (iii), and (iv) can be recovered by unloading (super-elastic effects) or heating (shape-memory effects). The passage of glissile dislocations through structural units is generally regarded as an irreversible process leading always to true plastic deformation.

Elastic stress during martensitic transformation

The martensitic structures formed in Cu-Mn alloys are very likely of the low-hysteresis, thermoelastic type commonly observed in shape-memory effect alloys[1]. Such martensites are extremely sensitive to stress and temperature in their formation. In general, whether during stress-induced transformation or deformation, these martensites respond to stress in such a way to best relieve the applied stress; this means that certain orientation-variants, specific transformation shears, etc. are favored over others. In single crystals it may be that the stress for stress-induced martensite formation is orientation-dependent. It has been pointed out that application of compressive stress to a single crystal will favor the FCT c-axis parallel to the stress direction while tensile stress will favor the FCT c-axis perpendicular to the stress

direction[6]. Stress-induced redistribution of existing martensite plates has been shown by direct (optical) microscopic observation; tension favors one set of plates, compression another; this is a feature of many thermoelastic martensitic microstructures[1]. (It should be noted that both thermoelastic and burst-type stress-induced martensites are observed in Cu-Mn alloys[2]).

Consider the most pertinent case, of a polycrystalline "austenitic" alloy (properly conditioned by aging for martensitic transformation when cooled): when the alloy is cooled through the Néel temperature (T_N), each austenitic grain will transform FCC → FCT during antiferromagnetic ordering. Each grain will adopt a c-axis direction, and the overall arrangement of c-axis directions will be such as to provide greatest total stress-relief (mutual accommodation) in the material. In the absence of external stress the c-axis directions would be expected to be randomly oriented in space. Application of external stress during the transformation will affect the array of orientations of the c-axes; as mentioned previously, resolved compressive stress favors the FCT c-axis parallel, tensile stress the FCT c-axis perpendicular. This will cause the formation of a quasi-single crystal, from which martensite will form when cooled through M_S. The stress will also affect the array of martensite plate orientation variants formed within the FCT grains.

In the case of thermoelastic martensites, confusion may arise with regard to apparent plastic deformation vs. true plastic deformation. True plastic deformation is that which cannot be recovered by unloading or heating. Apparent plastic deformation refers to cases where unusually large strains are recovered totally or partially by unloading (superelastic effects) or by heating (shape-memory effects)[1].

Plastic deformation prior to aging

Plastic deformation prior to aging has been shown to decrease SDC for the same aging time[5]. This is consistent with the expected acceleration by the stress of the diffusional aging process to an overaged condition.

Plastic deformation prior to martensitic transformation (ausforming)

The production of dislocations in the high temperature phase before cooling through M_s (or M_d, if referring to stress-induced transformation) may be regarded as generally helpful to martensitic nucleation, and detrimental to martensitic growth, leading to finer microstructures.

II.C. NPS Program Goals and Milestones, FY 74, FY 75

On the bases of the surveys and analyses described in the previous section, it was determined that it was important to study in more detail each of the five cases of stress/deformation effects, as well as interactions between them, in order to ascertain mechanisms affecting SDC and methods leading to control and optimization of damping properties.

The chronology of goals and milestones, as originally set forth 28 December 1973, is listed below, together with actual completion dates and references to the appropriate sections of this report for results.

1. Initial evaluation of potential materials solutions to noise/vibration problems (state-of-the-art determination) (1 July 73 - 15 August 73). (Completed-Section II.A. of this report.)
2. Determination of availability of materials (metals and alloys) of interest; procurement of initial materials (15 August 73 - 30 September 73). (Completed-Section III of this report.)
3. Survey of methods of measuring the damping capacity of high-

damping ("quiet") metals (15 August 73 - 30 September 73). (Completed - Appendix A of this report.)

4. Laboratory metallurgical characterization of as-received materials (1 October 73 - 15 November 73). (Completed - see Sections III and IV of this report.)
5. Detailed analysis of physical-mechanical metallurgical parameters controllable in the quiet metals Cu-Mn and TiNi (1 October 73 - 15 November 73). (Completed - Section II.B. of this report.)
6. Laboratory determination of deformation and annealing (recovery, recrystallization, and grain growth) behavior of Cu-Mn alloys (15 November 73 - 31 December 73). (Completed - Sections III and IV of this report.)
7. Procurement of additional materials (Cu-Mn) for thermomechanical processing experiments. (Estimated February 74). (Completed.)
8. Initial laboratory determinations of damping capacity of candidate materials (Cu-Mn and TiNi alloys) via resonant bar technique (Kilohertz frequencies) (at Los Alamos Laboratory and Stanford University); evaluation of the worth of the resonant bar method. (Estimated completion March 74). (Completed January 74 - Sections III and IV of this report.)
9. Laboratory evaluation of applicability of pulse-echo apparatus (Dept. of Physics, NPS) to measurement of damping capacity (@ megahertz frequencies) of quiet metals. (15 January 74 - 30 March 74). (Completed - Sections III and IV of this report.)
10. Acquisition of torsion pendulum apparatus (low frequency) for measurement of damping capacity from NSRDC. (Estimated arrival February 74). (Completed February 74).

11. Laboratory set-up, calibration, and evaluation of torsion pendulum apparatus and method. (March 74 - June 74). (Completed March 74 - Sections III and IV of this report.)

12. Thermomechanical processing trials with Cu-Mn. (March 74 - June 74). (Presently in progress - Sections III and IV of this report.)

PLAN FOR CONTINUATION (through FY 75)

13. Metallurgical characterization of processed material. (March 74 - June 74). (Presently in progress.)

13.* Corrosion evaluation of Cu-Mn and Ni-Ti alloys (Presently in progress.)

14. FY 74 Report (30 June 74) to include:

    (a) Progress and data obtained from #1 - 13 above.

    (b) Summary of potential ship silencing applications for quiet metals (See Section V of this report).

    (c) Summary of present availability and pertinent associated properties of interest for these materials (corrosion, fabricability, etc.) to the extent that such information is presently known. (See Section V of this report.)

    (d) Conclusions derived from research to date.

15. Damping capacity measurements on thermomechanically processed material (1 July 74 - 30 August 74). Note: Measurement method to be decided by results of #8 - 11 above. (Presently underway - some data included in Section IV of this report.)

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* Addition to 28 December 73 list of goals and milestones.

16. Correlation of structure (#12-13): properties (#15) (1 September 74 - 30 September 74.)
17. Graduation of Mechanical Engineering degree student; M.E.M.E. Thesis, LT Norman Hills, USN (30 September 74).
18. Direct (microscopic) substructural observation on processed and tested samples (from #12-15 above). Note: Assumes acquisition of a TEM (transmission electron microscope) by this time.
19. Substructure (#18): properties (#15) correlations. (1 January 75 - 30 February 75.)
20. Consideration of effect of fatigue on damping of quiet metals in machinery applications. (1 January 75 - 30 February 75.)
21. Fatigue damaging/testing: damping measurements. (1 March 75 - 30 June 75, and beyond.)
22. Direct substructural (TEM) observations on samples from #21, and structure: property correlations. (1 April 75 - 30 June 75, and beyond.)
23. FY 75 Report. (30 June 75.)
24. Continuation of #21, 22.
25. Extension of initial damping measurements (#15) to include the effects of applied static stress and/or temperature. (1 July 75 - 30 September 75.)
26. Consideration of specific design problems, i.e., applicability to present machinery, necessary redesign, trade-offs, etc. (1 October 75 - 30 November 75.)
27. Design and construction of a model machine, including methods of vibration and/or noise analysis, and involving application of quiet metal components. (1 November 75 - 30 January 76.)

28. To be announced, depending on results from earlier studies. The details and extent of tasks #20-27 (i.e., activities beyond 1 January 75) are also subject to major modification, dependent on results obtained from earlier work.

III. Experimental Methods (Mech. Eng. Degree Thesis Research, LT N. Hills)

A. Material

It was determined that at present there are two primary suppliers of Cu-Mn-based high damping alloys. An alloy known as "Sonoston" (nominally 37 Cu, 54.25 Mn, 4.25 Al, 3 Fe, 1.5 Ni) is produced by Stone Manganese Marine Ltd., London, while "Incramute" (nominally 58 Cu, 40 Mn, 2 Al) is marketed through INCRA (International Copper Research Association), New York. Both organizations graciously contributed sample material for this study. In addition, NSRDC, Annapolis, Maryland, supplied quantities of excess "Sonoston" alloy from earlier studies in that laboratory [(2)].

B. Recrystallization and Grain Growth Trials

Both of the commercial Cu-Mn-base materials mentioned above were solution treated by holding thirty minutes at 800°C and water quenching. Samples were cold-worked by rolling 5, 10, 30, 50, and 70% of the original thickness. Annealing treatments of thirty minutes duration were carried out over the temperature range 400°C-800°C. The annealing response was determined by Rockwell B-scale hardness readings and selected metallographic examinations.

C. Metallography

All metallographic specimens were prepared as follows: 1. Sand on 0 grit emery paper; 2. Sand on 3/0 grit emery paper; 3. Polish on 3 micron diamond dust wheel;

4. Polish on 1 micron diamond dust wheel; 5. Polish on .05 micron alumina wheel. 6. Alcoholic ferric chloride etch (100 ml. Ethanol, 5 gm. FeCl, 2 ml. HCL). Photomicrographs were taken with a Zeiss photomicroscope with automatic exposure device.

D. Stress-Age-Quench (SAQ) Apparatus

A BLH Baldwin Testing Machine (essentially a creep-rupture rig) was modified to allow aging and/or quenching of torsion pendulum/tensile specimens while under stress. A Marshall Tube Furnace was arranged vertically with a thin-wall steel tube placed inside (See Figure 4). This arrangement allowed the specimens to be aged and/or quenched in the furance with simultaneous stress application.

Two basic aging procedures were employed initially. One of these involved application of zero stress until the end of the aging period at which time the specimen was loaded axially to a given percentage of the yield stress and immediately quenched. A second scheme involved loading during the entire aging period, followed by quenching with or without stress.

E. Damping Capacity Measurement: Torsion Pendulum

A torsional pendulum originally built and used by the U. S. Bureau of Mines, Rolla, Missouri, was obtained from NSRDC, Annapolis, Maryland, to whom it had been loaned several years ago. This instrument was the primary device used to evaluate damping capacity (as a function of thermo-mechanical processing) in the early stages of this investigation. (See Figure 5.) The specimens were bars, seven inches long, with

a five inch test section machined to .200 inch diameter (See Figure 6).

The torsional vibration amplitude was measured by a strain gage on the specimen. The strain gage output was amplified and visually presented by a Honeywell Visicarder. Calibration was accomplished by application of known torsional moments by means of a string-weight-pulley system.

The SDC (specific damping capacity) was calculated from:

$$SDC = \frac{A_n^2 - A_{n+1}^2}{A_n^2} \quad 100$$

where A_n and A_{n+1} represent the amplitudes of successive vibration peaks.

F. Damping Capacity Measurement: Pulse - Echo (MHz) Apparatus

It was considered desirable to also experimentally evaluate alternate techniques available to measure damping properties of high-damping materials. The principles of various techniques are discussed in Appendix A. Of particular interest was the measurement of damping properties at higher frequencies than available with the (very low frequency) torsion pendulum. As part of this effort, an ultrasonic pulse-echo apparatus was adapted and evaluated. This apparatus had been previously used in the NPS Physics Department to measure sound velocities and elastic constants in metallic single crystals. The equipment may also be used without modification to measure signal attenuation in polycrystalline alloys from which damping capacity can be directly calculated.

The specific apparatus provided for the generation and detection of pulses of ultrasonic specimen excitation of MHz frequencies. These pulses propagate from end to end in right circular cylinder specimens. A Matec generator/receiver was used with a single quartz transducer bonded to one specimen end (see Figure 7). This single transducer acts as both driver and pickup for echoed pulses. The reflected pulses are amplified and presented on an oscilloscope. Initially, 0.25 inch diameter, 1.0 inch long specimens were prepared with parallel polished ends and were driven using an x-cut piezoelectric crystal.

Attenuation (ultrasonic damping) was found to be so high in these materials that, using the indicated specimen geometry, echos could not be detected at any pulse power level. For this reason, shorter specimens driven by larger transducers are currently being prepared for evaluation. If successful, the pulse-echo technique will be a simple measurement method, and will be employed more extensively to measure damping properties as a function of thermomechanical processing in the Cu-Mn-base alloys (in parallel with torsion pendulum measurements).

G. Damping Capacity Measurement: Resonant Bar (KHz) Method

In addition to the techniques for damping capacity measurement mentioned above, several specimens (right circular cylinders 0.25 inches in diameter and 4 inches long) were prepared and taken to Los Alamos Scientific Laboratory, Los Alamos, New Mexico, where Dr. P. Armstrong carried out measurements on an existing resonant bar device of the type normally used to determine Young's modulus. Results have been tabulated in Figure 8.

IV. Experimental Results and Discussion (Mech. Eng. Degree Thesis Research, LT N. Hills)

A. Recrystallization and Grain Growth

Typically, the effect of prior cold work on recrystallization response results in a set of curves such as shown schematically in Figure 9. The experimental curves for "Sonoston" (Figure 10) and "Incramute" (Figure 11) differ from this typical behavior due apparently to the superposition (in some cases) of an age-hardening response on the expected softening effects of recovery, recrystallization, and grain growth. This was not unexpected since the annealing temperatures were within a two-phase field.

A very unusual annealing behavior for the alloys is illustrated by Figure 10 in which the recrystallization temperature apparently increases with increasing prior cold work in contrast from the usual inverse relationship between recrystallization temperature and prior cold work. From this one might conclude that more thermal energy is necessary to initiate the atomic rearrangements of recrystallization for larger amounts of cold work which is not sensible. It is believed that this unusual response must, in fact, be due to the effect of simultaneous precipitation (strengthening) processes in the alloys during the annealing periods. This type of effect is more clearly defined for the Incramute annealing curves (Figure 11).

B. Aging Effects on Damping Properties

It was found in early aging trials that the standard aging program recommended by INCRA (5) (400°C for nine hours per inch of section thickness) must not be literally interpreted. Standard torsion pendulum samples (0.2 inches in diameter) had to be aged

eight hours to obtain maximum damping (see Figures 12 and 15-17). Aging at 450°C reduces the time-to-maximum-damping to two hours with a lower absolute value of the maximum SDC (see Figures 13 and 15-17).

SDC was normally measured at surface shear stresses of 1000, 5000, and 10,000 PSI. The SDC that can be developed is clearly significant. For example, a specimen of "Incramute" aged eight hours at 400°C produced torsion pendulum SDC values of 27, 39, and 57% at 1000, 5000, and 10,000 PSI respectively. Figure 18 allows a comparison of the characteristic torsion pendulum outputs for "Incramute" in the aged high damping condition versus the low-damping solutioned form.

Because of physical limitations of the torsion pendulum, some aged specimens could not be twisted enough to obtain 10,000 PSI surface shear stress, as they became quite "rubbery" after conditioning by aging and quenching. Those specimens which demonstrated this behavior exhibited high damping. The behavior was such as to belie apparent changes in shear modulus with aging. The general trend was for the modulus to apparently decrease with aging time at a given temperature, then increase again. This behavior is consistent with the observations of Section II.B. regarding the significance of aging reactions in Cu-Mn alloys.

Briefly summarized, specimens with optimum conditioning by aging (for high SDC) would be most highly martensitic; the martensitic structure reflects an apparently lower modulus (rubbery behavior) for the material under stress because of recoverable deformation mechanisms that are not truly elastic

(in the normal sense of bond stretching). This is typical of so-called thermoelastic martensites found in shape-memory-effect alloys[1].

It has been reported that for the binary Cu-Mn system there is approximately 6% linear shrinkage with aging. In view of the observations in Section II.B. and above, this might be interpreted as a manifestation of shape-memory-effect behavior. In our studies, sample length was monitored during aging. Machined "Incramute" torsion pendulum samples were observed to shrink only slightly when as-received plate material (apparently aged to the optimum SDC condition) was re-aged after re-solutioning. Shrinkage of 0.3 to 0.4% was observed to occur very early in the aging process before any significant damping capacity is developed. Such shrinkage was also observed in a sample stress-aged while axially loaded in tension to 60% of the yield stress.

Damping properties obtained from the resonant bar technique are unfortunately not directly translatable to SDC. The general difficulty is that values obtained are unique to the particular experimental arrangement and specimen geometry so that only relative correlations can be made. In the present case a reference sample of hard-drawn copper was used. "Incramute" and "Sonoston" samples (in the as-received condition) damped approximately six times as well as hard-drawn copper by this means of comparison (see Figure 8).

An interesting observation can be made on the Sonoston resonant bar data (Figure 8) which was obtained at two different vibration frequencies. It is notable that a decrease of 9 Hz

driving frequency resulted in a tenfold increase in vibration amplitude. This reaction is characteristic of a nonlinear hardening spring (Figure 19), involving asymmetric resonance peaks (see Figure 8 data). Because of the magnitude of the jump phenomena, it is believed that the nonlinearity is not too great in this case.

Initial attempts with the ultrasonic pulse echo apparatus were relatively unproductive due to incapability to drive a signal through the unusually high-damping specimen material. It is hoped that the use of thinner samples and larger driving crystals will overcome this problem.

V. Engineering with Quiet Metals - Suggestions

It is appropriate at this point to ask of what use (to the Navy) might be an alloy with SDC greater than 30-40% and other reasonable engineering properties. The following brief discussion is intended to provide information regarding this and related questions.

One can compile an extended list of potential (Naval) applications of quiet metals. Applications that might benefit from design integration of high-damping alloys include (see Figure 20) ship, submarine, and torpedo propellers, machinery gears or gear webs, mating friction parts, cladding for virtually any noisy part, helicopter gears, absorption plugs in noisy machine components of all kinds, piping isolators, machine components subject to minor impact contacting, compartment wall liner sheets, ad infinitum.

Some relevant engineering properties for various alloys were given in Figure 1. A more detailed summary of the properties of high-damping alloys are given in Figure 21 along with the properties of two low-damping

reference materials for comparison. The uniqueness of Cu-Mn-base alloys is that they combine high damping capacity, high tensile strength, and ductility; they are roughly comparable to mild steel or cartridge brass in strength.

With regard to fabricability, Cu-Mn-base alloys such as "Incramute" are readily hot and cold workable[6], comparable to cartridge brass. However, heat treatment will normally be necessary after cold working to re-establish high damping properties, especially if this working is done after aging. Working between the solution step and aging step will not necessarily degrade damping properties attainable by subsequent aging, but will change the kinetics of the aging reaction and, therefore, change the required aging treatment in an unknown way. Because of uncertainties associated with this effect, it would be simpler to resolution and re-age in most cases. Details of the interacting effects of deformation and aging on structure and damping properties were discussed in Section II.B. of this report. It is clear that careful control of thermomechanical variables will be necessary to obtain optimum damping in all cases. It should be noted, however, that Cu-Mn-base alloys can exhibit substantial and uniquely high damping even without excess care.

Castings of Cu-Mn-base alloys will normally be able to attain quite high damping values without subsequent thermal treatment. However, the alloys have high solidification shrinkage which can cause "piping" and lead to "hot-tearing" problems when castings are made in conventional molds. Successful casting requires careful mold design and pouring practice. Heat treatment after casting, though not of necessity, will commonly be able to induce some enhancement of damping properties.

Corrosion properties of Cu-Mn-base alloys such as "Incramute" in sea water are not particularly good. The alloys are very susceptible to

"parting" ("dezincification" - type attack) and stress-corrosion-cracking in NaCl environments, and long-time applications involving sea water exposure are precluded unless cathodic protection or coating is provided. However, it is considered that there are numerous excellent Naval applications not involving sea water exposure which can benefit greatly from the application of "quiet-metal" type alloys. It should be noted that other "quiet metals" do not necessarily share the sea water corrosion deficiencies of Cu-Mn-base alloys. "Nitinols", in fact, are considered to have quite superior corrosion properties.

An important limitation to the usage of Cu-Mn-base and other quiet metals is an upper temperature limit for damping application. At temperatures typically around 50-200°C, damping properties decay due to reversion of the low temperature martensitic (high damping) phase to the high temperature equilibrium (low damping) phase. The temperature at which high damping degrades varies with alloy composition; the damping is recovered on re-cooling below the transition temperature. Damping capacity in Cu-Mn-base alloys is commonly observed to slowly degrade at room temperature, but not to the extent that useful damping is lost; high damping can be restored in this case by elastic stressing; this type of degradation is not observed in Ni-Ti alloys.

As is the case for nearly any advanced and sophisticated materials development, the accentuation of one particular engineering property to unusual levels will involve either (i) trade-offs with other properties in terms of optimizing conditioning treatment, or (ii) acceptance of inherent weaknesses in certain property areas in order to gain the unusually high values in one area. This philosophy clearly applies to the case of applying the unique damping properties of Cu-Mn-base and

related alloys. For example, while Cu-Mn-base alloys will, in general, require greater care during fabrication operations, there is a significant payoff in damping properties that cannot otherwise be realized in alloy materials with good engineering properties.

The metallurgical variables encountered in Cu-Mn-base alloys are quite unique, and make any reference to "normal" behavior and treatment irrelevant. Selection for applications should be made only with thorough consultation on the unique metallurgical features and requirements of these alloys.

VI. Summary

A survey of high-damping materials shows that two basic alloy systems, Ni-Ti and Cu-Mn, currently have been developed to the point of commercial availability and general engineering attractiveness. Alloys from both systems have the potential of wide application for noise/vibration reduction. The damping capacity of these quiet metals is so unusually high (SDC up to 50% or greater) that new methods of design integration for noise reduction may have to be developed.

The NPS research program in FY 74 has concentrated on the characterization of metallurgical factors (such as aging, elastic stress, and plastic deformation) which may affect (submicrostructure and therefore) damping properties in Cu-Mn-base alloys. Detailed investigations have been initiated into the recrystallization, aging, stress-aging, stress-quenching, and deformation responses of specific damping capacity (SDC) in the commercial Cu-Mn-base alloys known as "Incramute" and "Sonoston." Investigation of the first two metallurgical responses (recrystallization and aging) has been essentially completed. SDC above 50% has been produced as expected, measured via torsion pendulum. Factors

exactly controlling SDC are currently being pursued in the continuing program. It is clear that these alloys, if used in wrought form, will have to be heat-treated after working in order to re-establish high damping properties. Properly-designed castings should be able to develop reasonably high damping values without subsequent thermal treatment. Other alloys, such as the Ni-Ti-base "Nitinols" would characteristically not require as much thermal treatment as the Cu-Mn-base materials.

VII. References

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11. R. J. Wasilewski, "Elastic-Modulus Anomaly in TiNi," Trans. Met. Soc. of AIME, 233, 1691 (1965).

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Figure 1: Table of comparative properties of materials at room temperature

Material	SDC(%)	YS(KSI)	Density (g/cc)
Mg alloy (cast)	60	10	≈ 1.8
Pure Mg (wrought)	49		1.74
Cu-Mn-base alloys*	40	45	7.5
"55-Nitinol"*	40	25	6.45
High carbon alloy gray cast iron	19	25	
Pure nickel	18		8.9
Pure iron	16		7.86
TD-Nickel	14		
Martensitic stainless steel	8	85	
Gray cast iron	6	25	
SAP-Aluminum	5	20	2.55
Low carbon steel*	4	50	
Ferritic stainless steel	3	45	
Malleable, nodular cast irons	2	50	
Medium carbon steels	1	60	
Austenitic stainless steel	1	35	
1100 Aluminum	0.3	5	2.71
Al alloy 2024-T4	< 0.2	47	2.77
Ni-base superalloys	< 0.2	Range	≈ 8.5
Ti alloys	< 0.2	Range	≈ 4.5
Brasses and bronzes*	< 0.2	Range	≈ 8.5

* See Table 21 for more detailed properties.

Figure 2

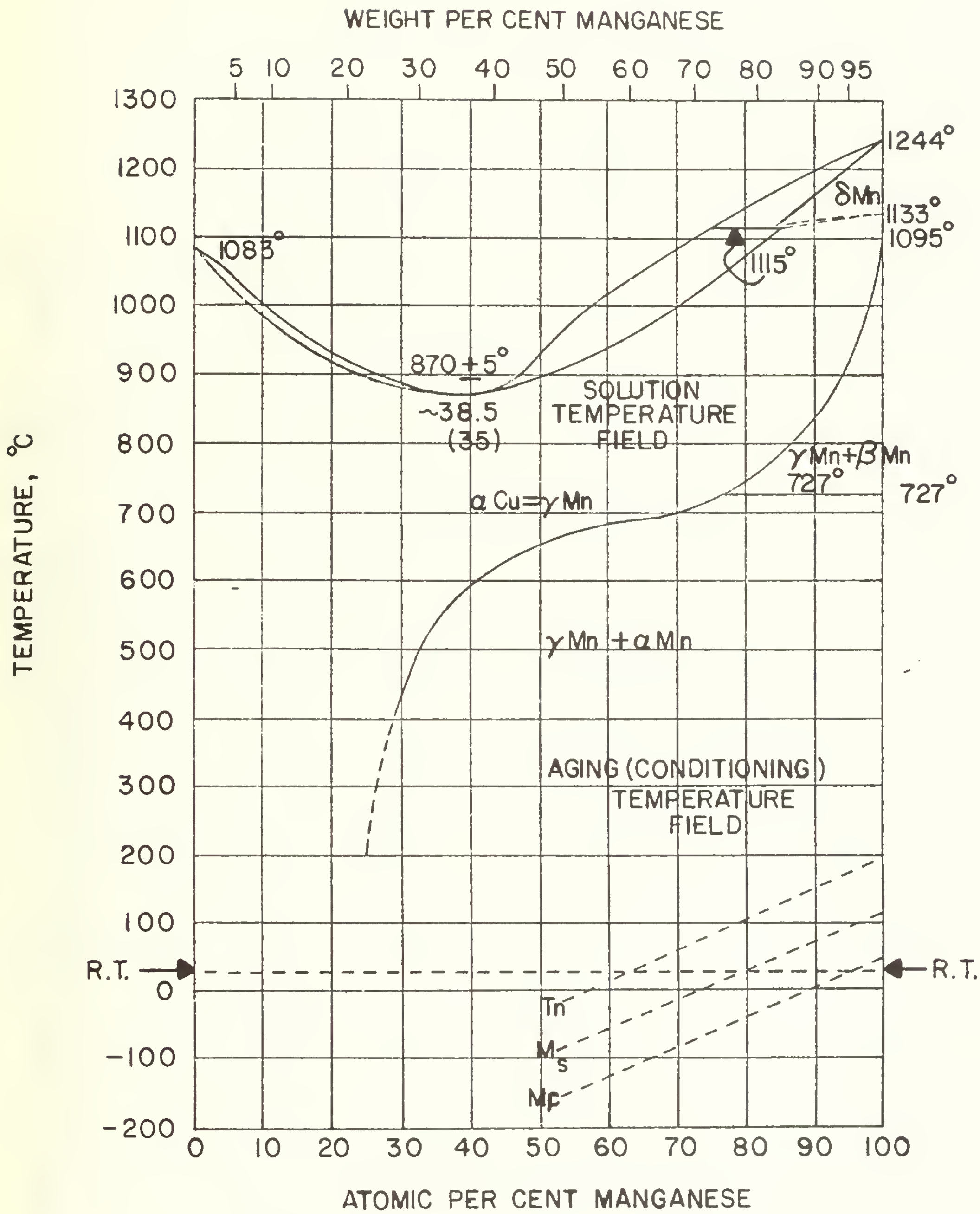

WEIGHT PER CENT MANGANESE
5 10 20 30 40 50 60 70 80 90 95
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
-200
TEMPERATURE, °C
1083°
1244°
δMn
1133°
1095°
1115°
870 ± 5°
~38.5
(35)
SOLUTION
TEMPERATURE
FIELD
γMn+βMn
727°
727°
αCu=γMn
γMn +αMn
AGING (CONDITIONING)
TEMPERATURE
FIELD
R.T.
R.T.
Tn
Ms
Mf
0 10 20 30 40 50 60 70 80 90 100
ATOMIC PER CENT MANGANESE

Figure 3: Summary of Heat Treatment Effects in Cu-Mn Alloys

Step 1: Solution treatment:

γ_{Mn} ($\equiv \alpha_{Cu}$) (A1:FCC)

Step 2: Quench from solution treatment temperature:

If < 80 w/o Mn: γ_{Mn} retained @ room temperature

If > 80 w/o Mn: γ_{Mn}
$\downarrow$
antiferromagnetic ordering, @ T_N
$\downarrow$
martensitic transformation @ M_s ($T_N > M_s$)

Step 3: Aging treatment (assuming alloy < 80 w/o Mn) (in two-phase region:

γ_{Mn}(A1:FCC) + α_{Mn} (A12: complex BCC))

Stage I: $\gamma_{Mn} \xrightarrow{\text{(initial)}} \gamma_{Mn}$ (Mn-enriched) (matrix) + "ω" (metastable Cu-rich precipitates, 100Å)

Stage II: $\xrightarrow{\left(\text{more time}\right)}$ γ_{Mn} (Mn-enriched (matrix) + "ω" + α_{Mn} (Widmanstatten precipitate) (small amount)

Stage III: $\xrightarrow{\left(\text{more time}\right)}$ γ_{Mn} (Mn-depleted) + $\overset{\text{dissolves}}{\cancel{\omega}}$ + α_{Mn} (equilibrium amount)

NOTE: The condition of Stage II is typically that leading to optimum damping; Stage III is overaged, i.e. no martensitic transformation of the γ_{Mn} matrix will occur on subsequent quenching - such will occur only if the matrix is conditioned to the necessary Mn-rich state by metastable "ω" precipitation.

Step 4: Quench from the aging treatment (assuming Stage II condition from Step 3 above):

γ_{Mn} (Mn-enriched) +	"ω" +	α_{Mn} (small amount)
$\downarrow$	$\downarrow$	$\downarrow$
antiferromagnetic ordering @ T_N		
$\downarrow$		
martensitic transformation @ M_s	retained ?	retained

NOTE: The martensitic transformation is triggered by the strain associated with the tetragonal distortion (FCC $\rightarrow$ FCT)of the antiferromagnetic ordering reaction; $T_N > M_s$.

Figure 4

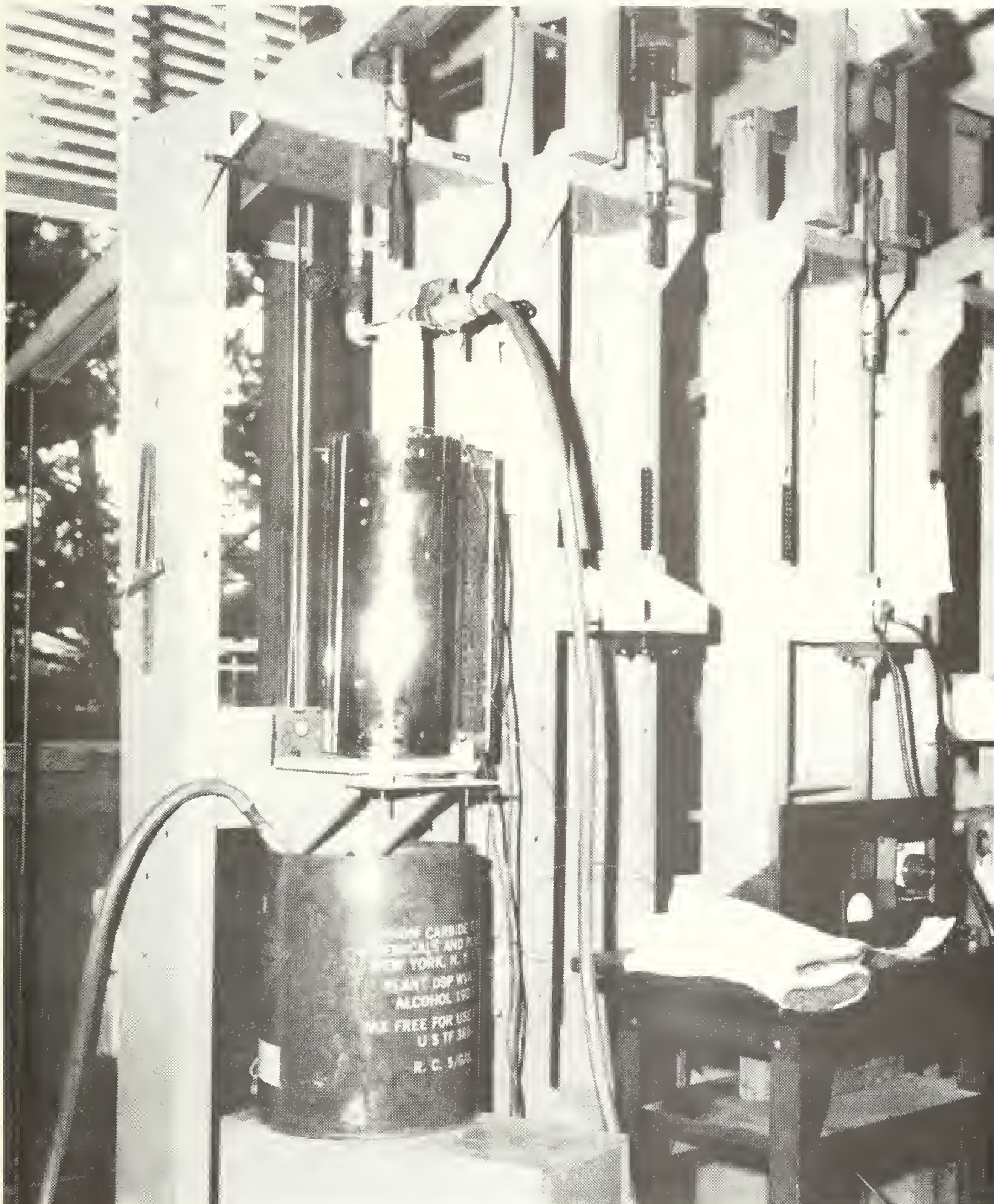


Figure 5

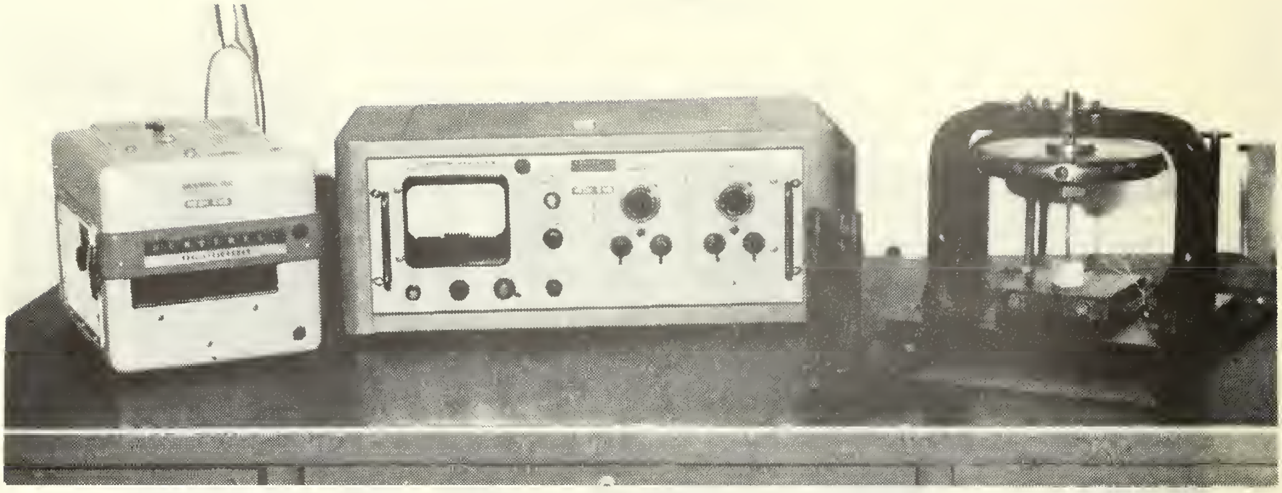


Figure 6

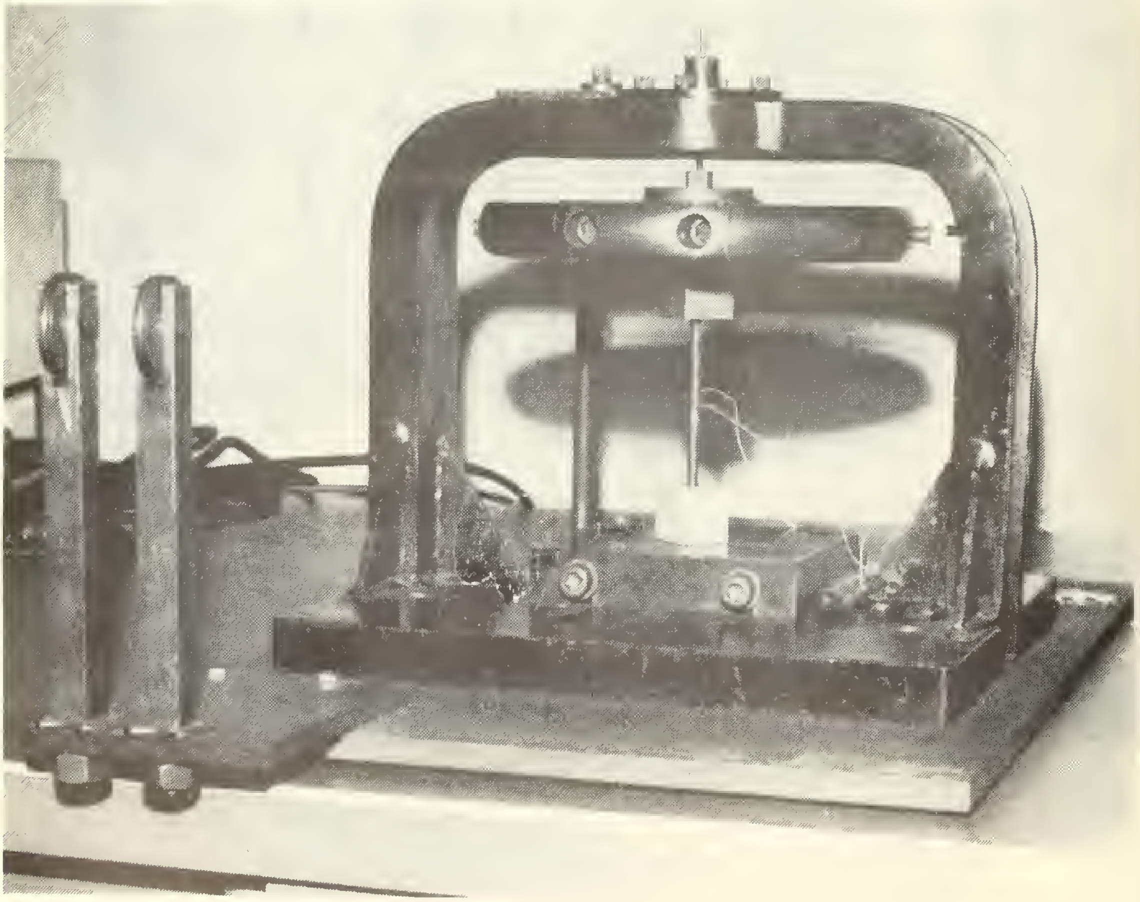


Figure 7

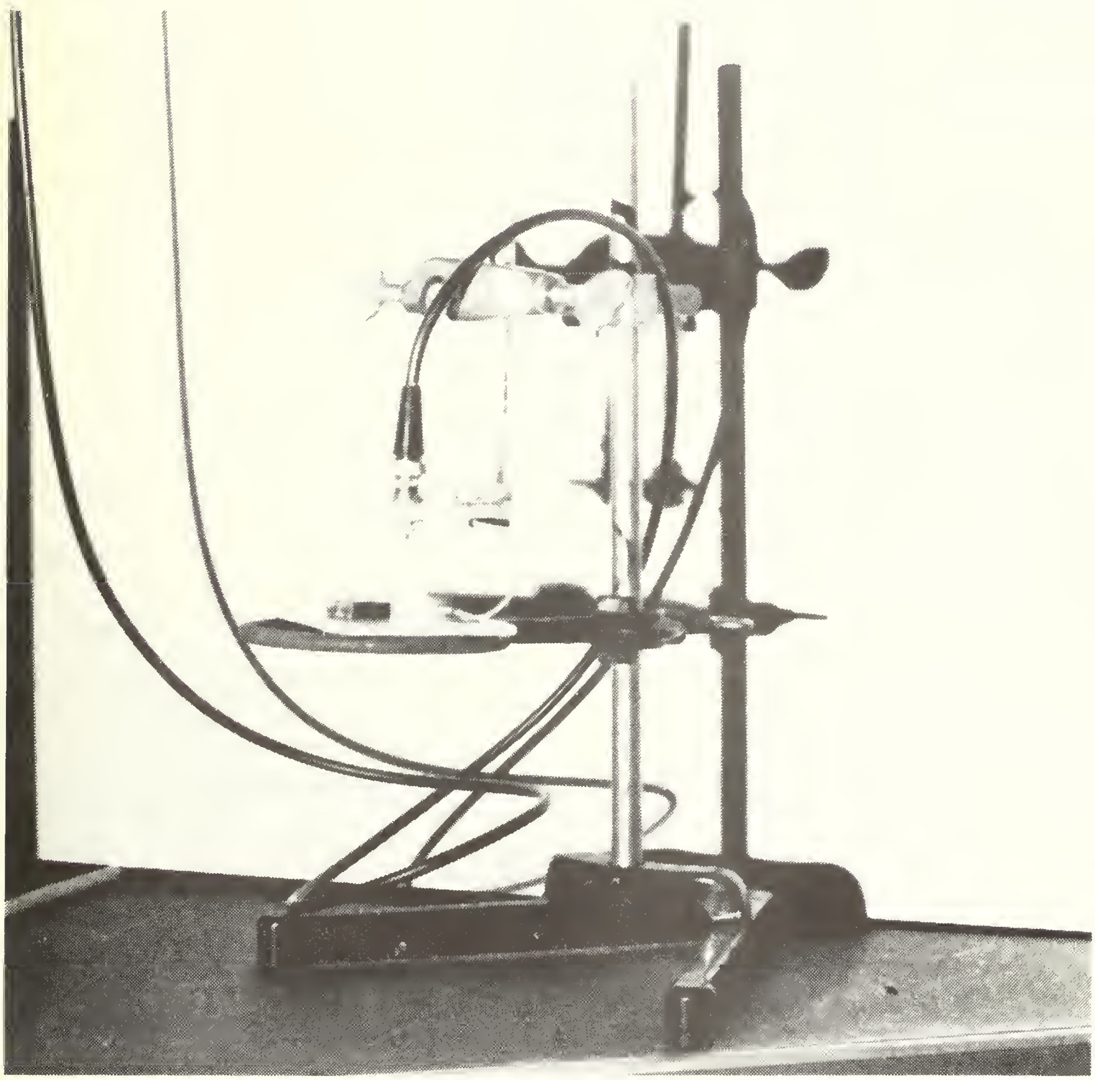


Figure 8: Table of Resonant Bar Damping Values *

Material	ℓ in	$\bar{d}$ in	W g.	ρ g/cc	f_ℓ Hz	$f\frac{1}{2}+$	$f\frac{1}{2}-$	E 10^6psi	tan α 10^{-3}
Incramute (longitudinal)	4.114	0.240	22.726	7.451	16806	16937	16716	13.333	7.59
Incramute (transverse)	3.919	0.239	21.422	7.435	17716	17862	17626	13.416	7.69
Nitinol	4.043	0.2505	21.1586	6.480	16896	16948	16874	11.319	2.53
Sonoston	4.0105	0.2515	23.186	7.102	16701	16830	16619	11.926	7.29
Sonoston*	"	"	"		16692	16794	16597	11.913	6.81
Copper hard drawn	4.503	0.2495	30.0920	8.341	16653	16674	16633	17.557	1.42

* Amplitude of vibration ten times previous measurement

$E = 3.7432 \times 10^{-4} f^2 \ell^2 \rho$ where

f= resonant frequency, Hz

ℓ= length, inches

ρ= density, g/cc.

$\tan\alpha$ = internal friction = $\frac{L_f}{\sqrt{3}\,f}$ where Δf = freq. difference at half amplitude

* Measurements made by P. E. Armstrong at Los Alamos Scientific Laboratory.

Figure 9

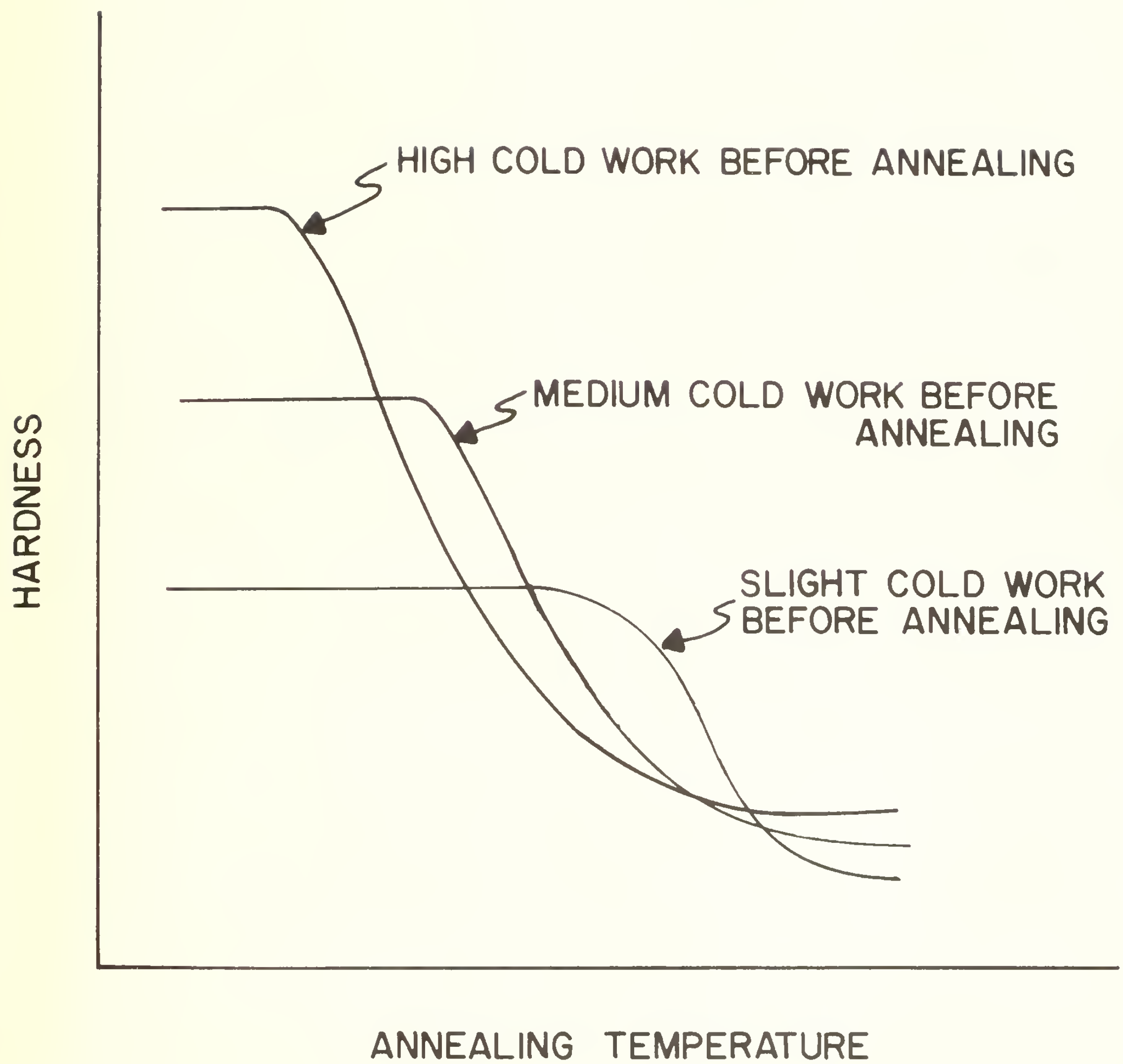

HIGH COLD WORK BEFORE ANNEALING
MEDIUM COLD WORK BEFORE ANNEALING
SLIGHT COLD WORK BEFORE ANNEALING
HARDNESS
ANNEALING TEMPERATURE

Figure 10

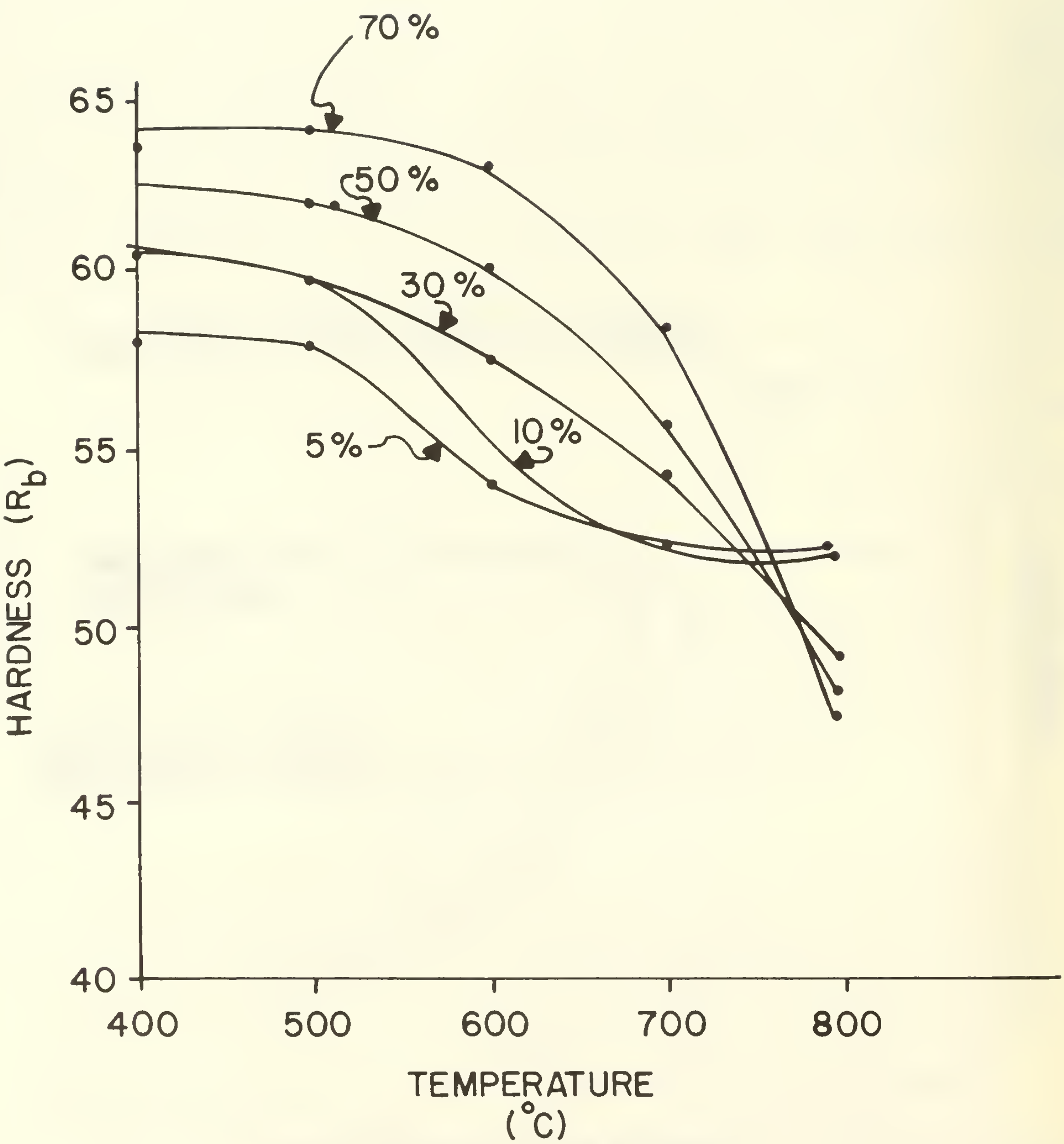

70 %
50 %
30 %
10 %
5 %
65
60
55
50
45
40
HARDNESS (R_b)
400
500
600
700
800
TEMPERATURE
(°C)

Figure 11

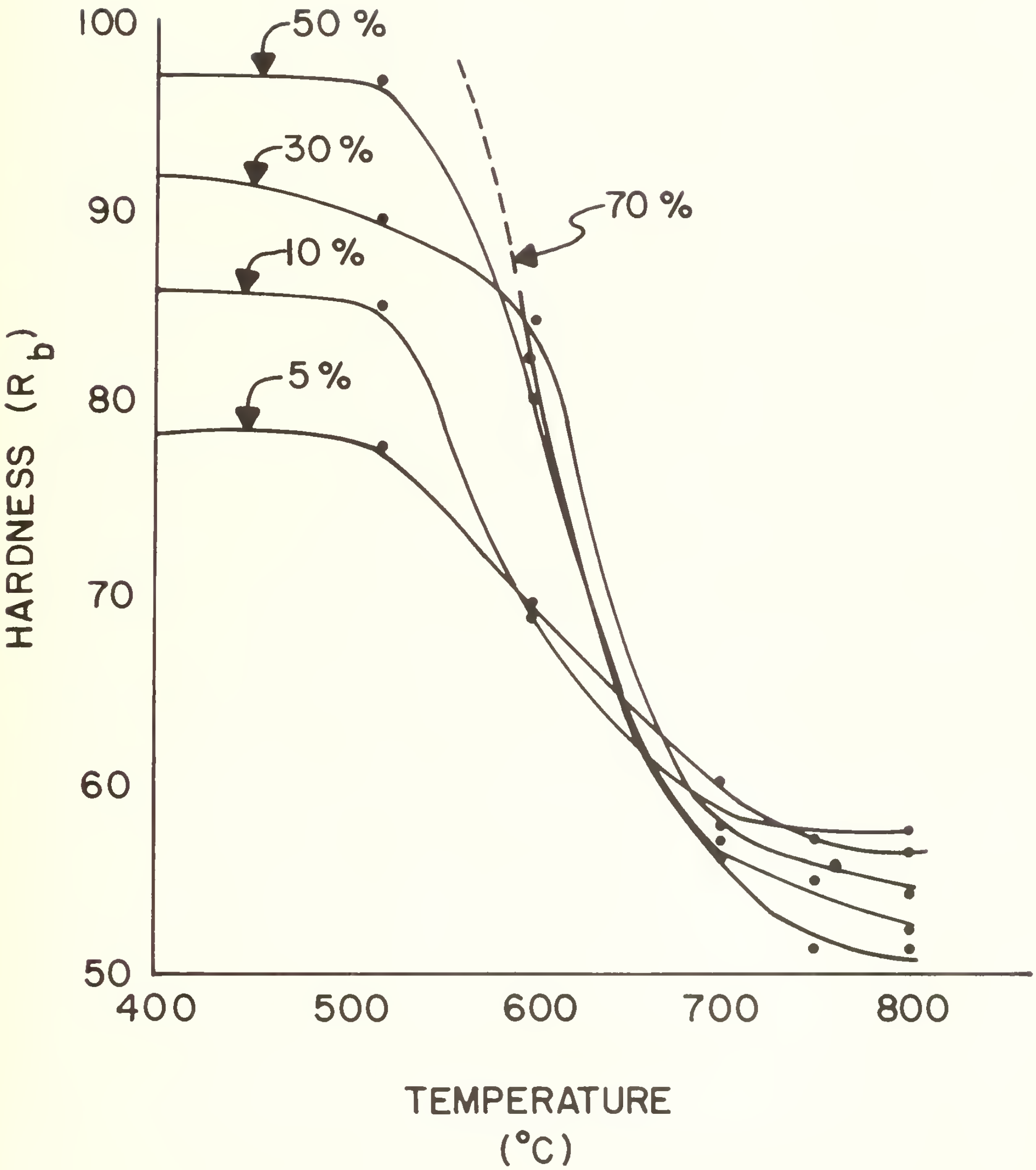

100
90
80
70
60
50
HARDNESS (R_b)
50 %
30 %
10 %
5 %
70 %
400
500
600
700
800
TEMPERATURE
(°C)

Figure 12: Table of SDC data for "Incramute" aged at 400°C

Time of Aging Temperatures hours	Surface Shear stress, PSI		
	1000	5000	10,000
2	5.63%	25%	8.69%
4	15.51%	12.7%	*
6	27.09%	31.69%	> 30.18%*
8	36%	40.49%	37.38%
10	10.24%	35.63%	> 40.28%*

* Could not physically twist the specimen enough to obtain 10,000 PSI surface shear stress.

Figure 13: Table of SDC data for "Incramute" aged at 450°C

Time of Aging Temperatures hours	Surface Shear stress, PSI		
	1000	5000	10,000
0.5	.4%	1.33%	1.96%
1.0	12.87%	11.70%	10.47%
1.5	19.47%	23%	24.4%
2.0	25.04%	25.12%	26.94%
2.5	13.4%	24.3%	26.2%

Figure 14: Table of SDC data for "Incramute" aged at 500°C

Time of Aging Temperatures hours	Surface Shear stress, PSI		
	1000	5000	10,000
0.5	6%	7.85%	8.75%
1.0	7.15%	6.9%	13.7%
1.5	5.58%	6.65%	11.2%

Figure 15

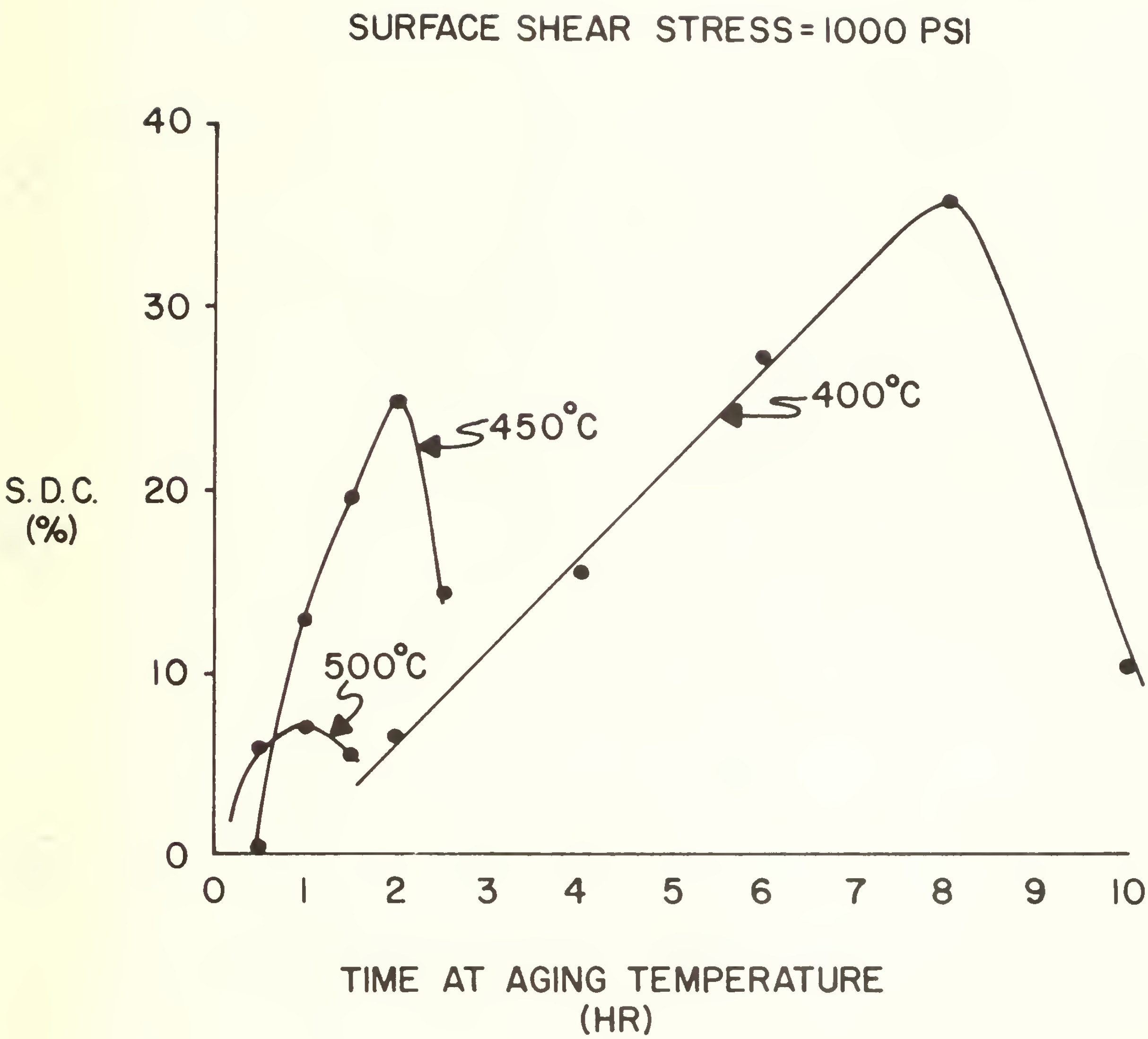

SURFACE SHEAR STRESS = 1000 PSI
S. D. C. (%)
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
450°C
400°C
500°C
TIME AT AGING TEMPERATURE (HR)

Figure 16

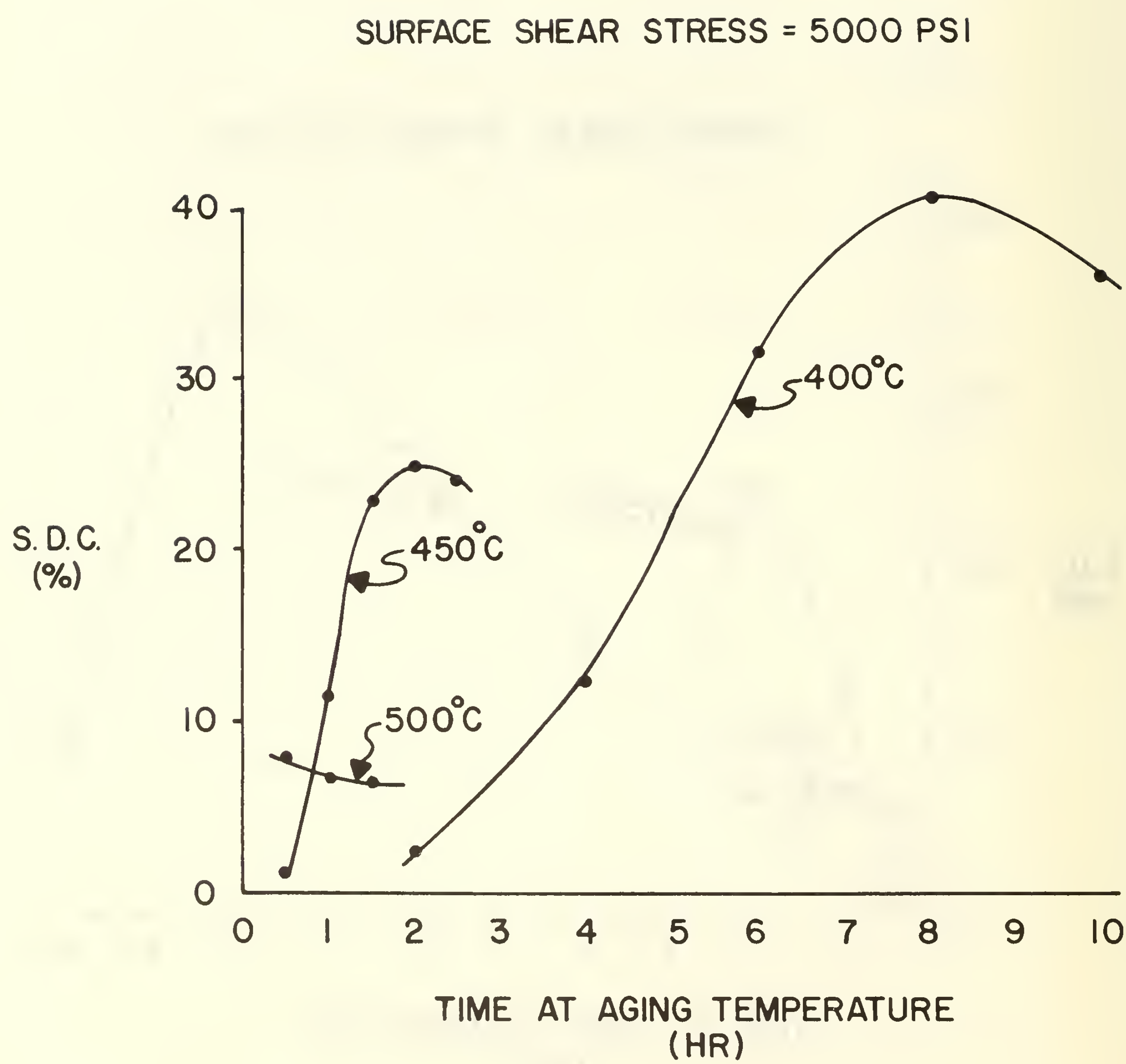

SURFACE SHEAR STRESS = 5000 PSI
S. D. C.
(%)
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
400°C
450°C
500°C
TIME AT AGING TEMPERATURE
(HR)

Figure 17

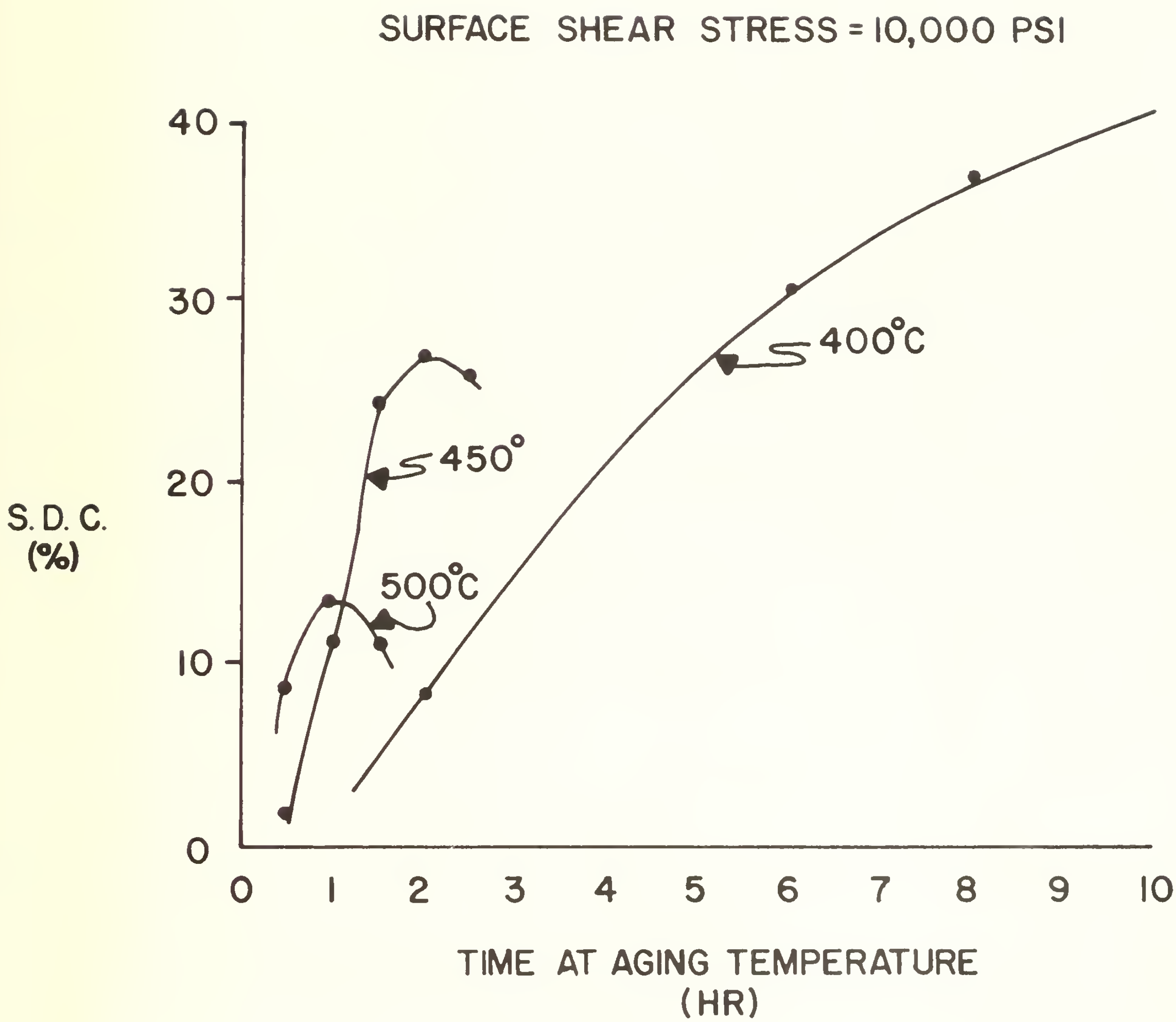

SURFACE SHEAR STRESS = 10,000 PSI
S. D. C.
(%)
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
400°C
450°
500°C
TIME AT AGING TEMPERATURE
(HR)

Figure 18a

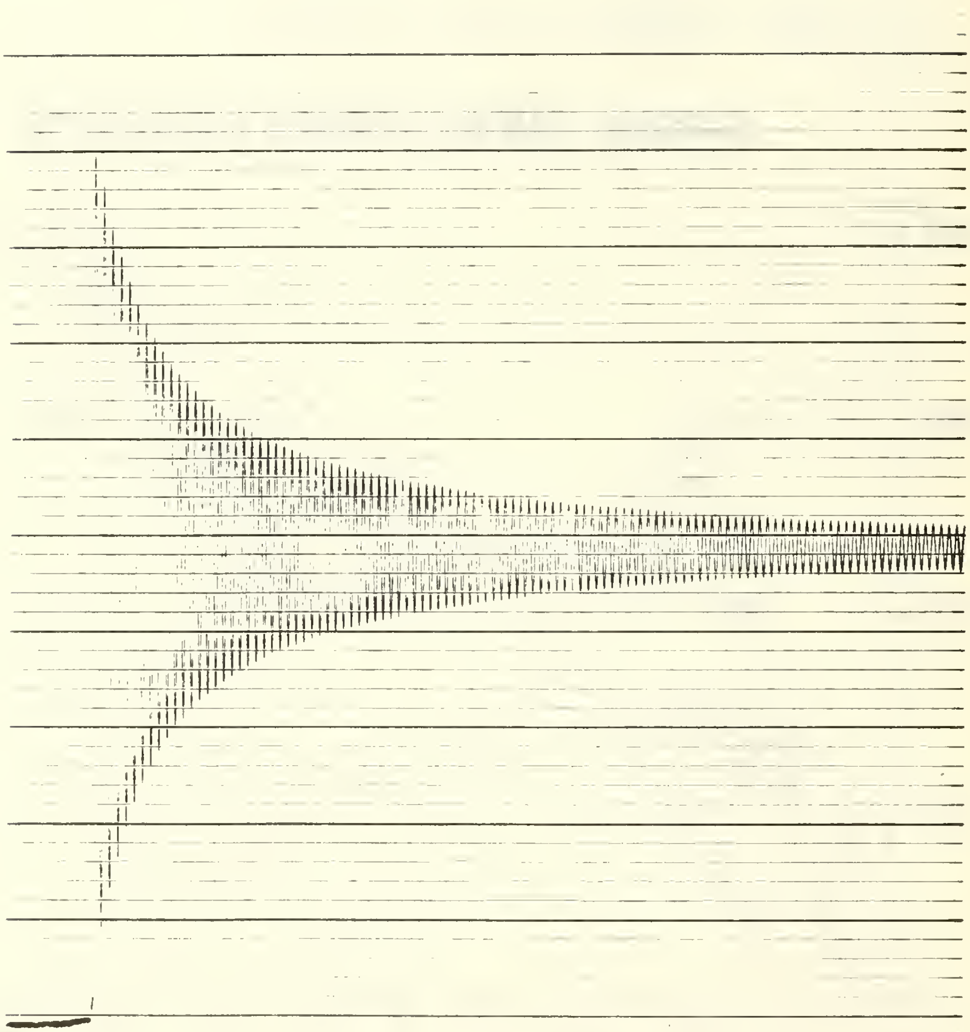


Figure 18b

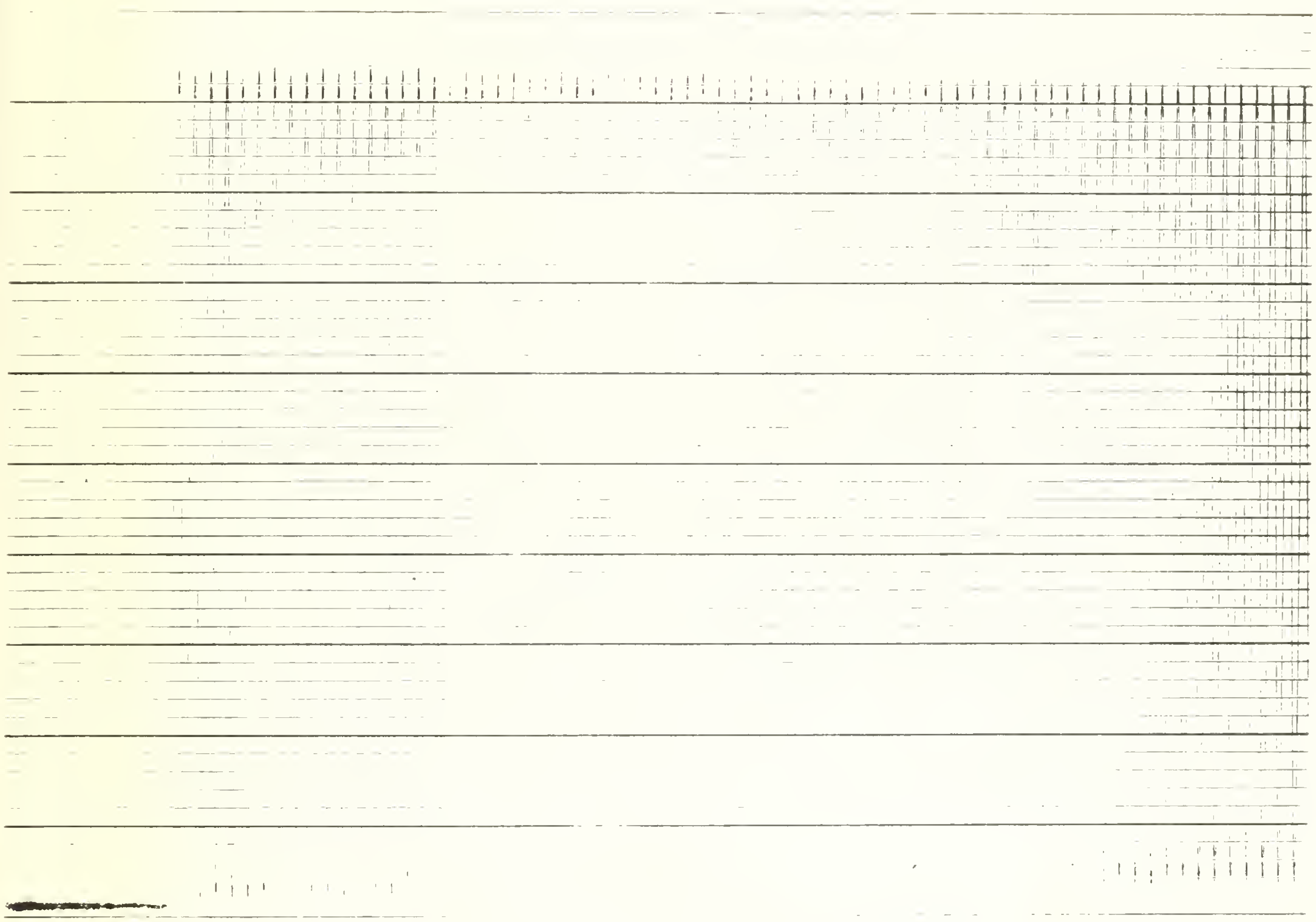


Figure 19

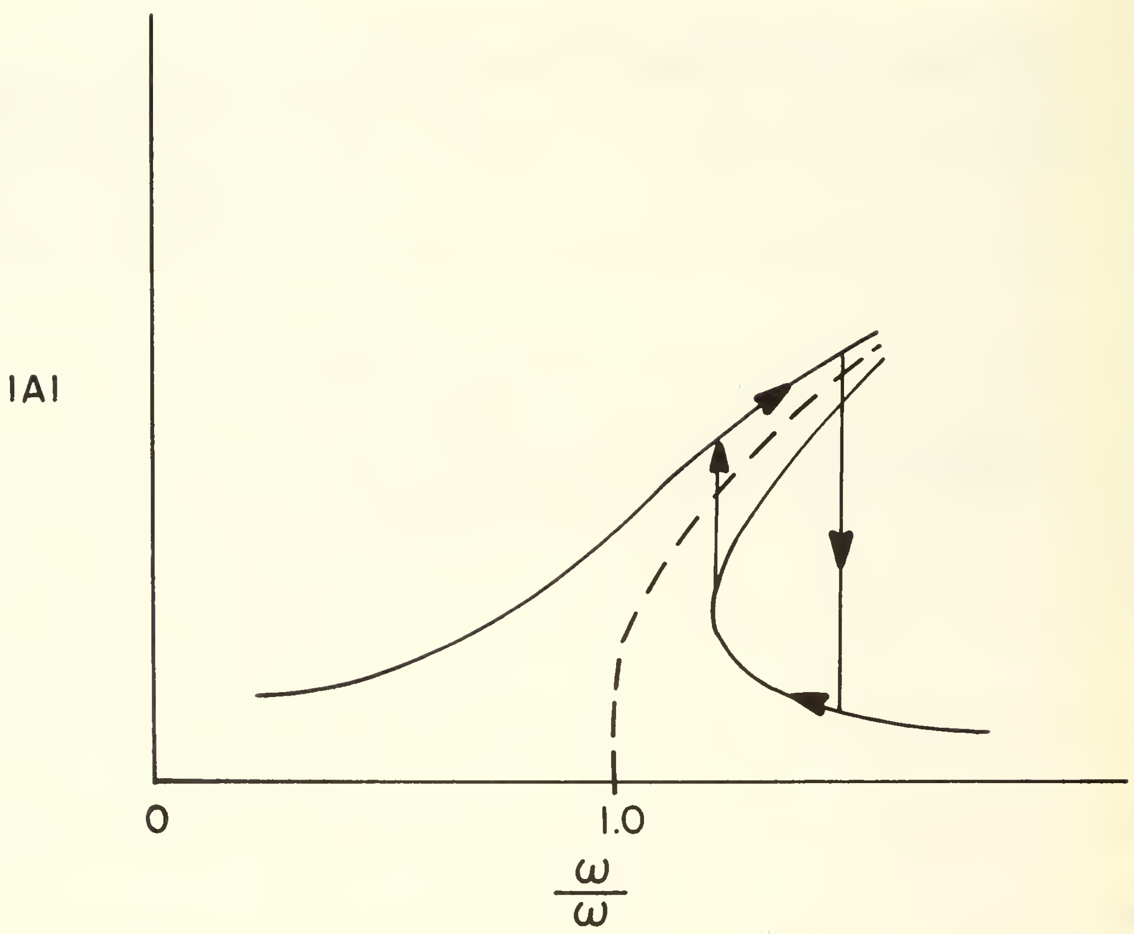


Figure 20: Potential applications of quiet metals

General:

Plug inserts to noisy machine parts

Cladding for virtually any noisy part

Reduction of resonant amplification factors

Attenuation of ringing

Machinery diagnostic techniques

Specific:

Gears and gear webs

Pump castings

Diesel engine parts

Brake discs

Wheel rims

Submarine/torpedo/ship propellers

Helicopter gears

Machinery frames and bases

Aircraft/missile structural members

Phonograph pickups/playing arms

Transducers

Office/textile/printing machinery components

Hi-fi audio microphone components

Bimetallic strips-control devices

Plates for tuning capacitors

Resistors

Hearing aid components

Movie camera gears, etc. etc.

Figure 21: Table of physical and mechanical properties of high-damping Cu-Mn-base and Ni-Ti-base alloys, with reference properties for low-carbon steel and cartridge brass

		"Incramute"[1]	"55-Nitinol"	Mild Steel[2]	Brass[3]
SDC	%, @ 5000 PSI	40	40	4	0.2
UTS	KSI	85	125[5]	70	47
YS	KSI	45	25[5]	50	15
Ductility	% elong.	30	60[5]	30	50
Modulus, E	PSI x 10^6	12	12.5[6]	30	16
Density	g/cc	7.49	6.45		8.53
Melting point	°F(°C)	(196)	2390 (1310)	2775	1750
Thermal expansion[4]	α μ-in/in°/C	22.5	10.4	8.4	11.1
Fatigue strength	KSI for 10^8 cycles	20	70[7]		14
Hardness	R_B (BHN)		90	(140)	65
Thermal conductivity	K(BTU/ft/hr/°F)			27	70
Electrical resistivity	μ-ohm-cm		80		6.2
Electrical conductivity	% IACS@70°F				28
Specific heat	BTU/lb/°F@70°F			.10	.09
Magnetic permeability			< 1		

1: in optimum damping condition

2: normalized 1025 steel

3: 70-30 (cartridge) brass, annealed

4: mean coefficient, 25°C-1000°C

5: exact values dependent of test temperature relative to transition temperatures

6: of high-temperature phase

7: 10^7 cycles

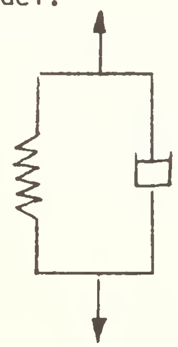
Appendix A: Survey of Methods of Measuring the Damping Capacity of High Damping Materials

The following section discusses various methods of experimentally determining damping capacity, (i.e. internal friction), of homogeneous materials. Commonly used experimental techniques are explained. The technique considered the most appropriate for high damping capacity materials is presented in detail.

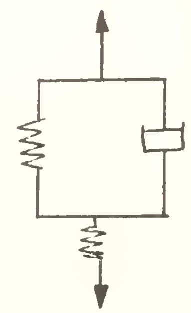
Included is a brief discussion of the theoretical model and the parameters available for expressing damping capacity.

Theoretical Model

For a material to exhibit a measurable damping capacity, the modulus of elasticity must be expressed as a function of time in a rheological behavior model. Typically, damping behavior is simply modeled as a linearly damped oscillator. A two-element system of dash pot and spring, the Kelvin-Voigt model, allows a complex representation of the modulus of elasticity. The standard linear solid, a three parameter model, permits greater isolation of the real and imaginary components of the modulus of elasticity. This advantage is gained at the expense of greater complexity in calculations. Bert (7) discusses both these models and others in detail including a nonlinear model.



Kelvin-Voigt model



Standard linear solid model

Variation based on the Kelvin-Voigt model will be considered. The basic equation of motion for the forced and free vibration modes is

$$m\ddot{u} + c\dot{u} + ku = A$$

where for free oscillation $A = 0$, and for forced sinusoidal oscillation $A = \bar{F}e^{i\omega t}$. As a result, u, displacement, is defined as

$$u = \bar{F}[(k - m\omega^2) + i\omega c]^{-1} e^{i\omega t}.$$

From this equation it can be seen, from the complex component, that damping capacity will be a function of frequency where

$$C_d' = \pi c$$

Lazan [8] has shown that this is not always the case; that phenomenologically damping is not always dependent on ω, frequency.

Kimball and Lovell [9] removed c, the velocity or rate dependent factor and replaced k with $\bar{k}'$, where

$$\bar{k}' = (k + ib).$$

This conceptually placed damping materials in the strain regime vice the viscoelastic regime. Now the equation of motion is expressed by

$$m\ddot{u} + (k + ib)\,u = \bar{F}e^{i\omega t}$$

$$\text{and } \bar{u} = F[(k - m\omega^2)^2 + b^2]^{-1/2} e^{i\omega t}$$

One measure of damping, the amplification factor, AF', shows that this model is now frequency independent with regard to damping capacity.

$$AF' = \bar{u}/u_{static}$$

$$u/static = F/k', \text{ where } k = (k^2 + b^2)^{1/2}$$

$$\text{now; } AF' = \frac{(k^2 + b^2)^{1/2}}{[(k - m\omega^2) + b^2]^{1/2}}$$

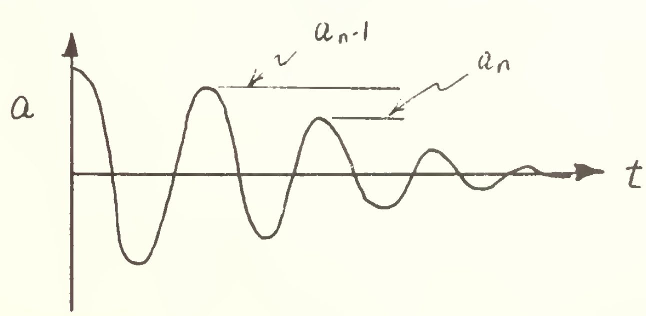
<u>Measures of Damping</u>

Material self-damping modes in alloys vary greatly. Entwistle[10] has cataloged over twenty microstructural energy absorbing mechanisms. Considering this variety, particularly with regard to magnitude, it is clear that one quantitative measure of damping is insufficient for all alloys.

Four common quantitative measurement techniques will be discussed. Their discussion and applicability is in the appropriate order for materials of increasing damping capacity.

1. Logarithmic decrement

    This indicator is commonly obtained from free oscillation in the flexural mode. The experiment usually involves a torsional, bending, or axial vibratory response to an initial deflection of the free end of a member. Amplitude of vibration is measured and plotted in continuous time frame.



The ratio of the amplitudes of any two adjacent peaks is formulated to express a measure of the decay rate.

$$\delta = \log \frac{an}{an-1}$$

δ, the log decrement, is nondimensional and normalized. From this variable one may directly calculate specific damping capacity.

2. Specific Damping Capacity

Another form of expressing the amplitude decay for the same experimental conditions described above is:

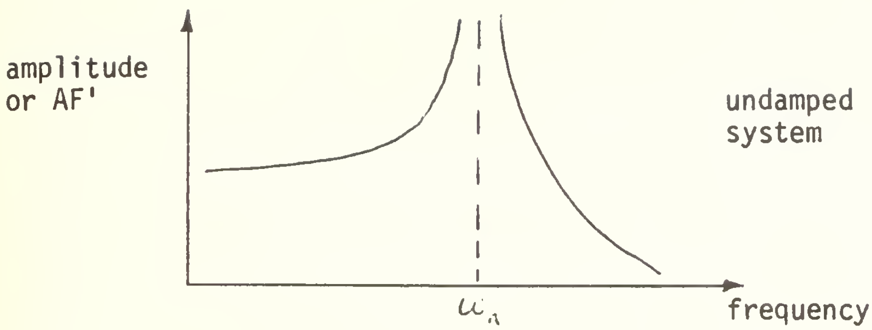
$$SDC = \frac{A_n^{\,2} - A_{n+1}^{\,2}}{A_n^{\,2}} \qquad 100$$

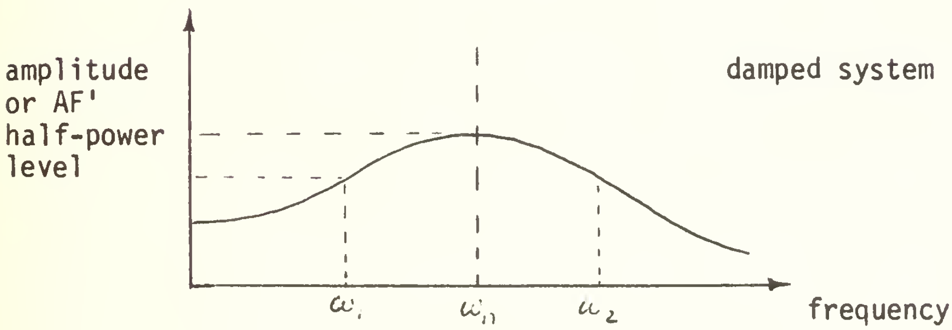
where SDC is the specific damping capacity, expressed as a percentage. It attempts a direct relation to absorbed energy by using the square of the amplitude, a tacit assumption for all materials.

The next two indicators of damping relate to forced vibration.

3. Resonance Curve Breadth Factor

This parameter is a measure of the diminishment of the amplitude response curve for frequency variation.





The band width is measured by defining a point of relative amplitude, the half-power points where,

$$a = \frac{\sqrt{2}}{2} \text{ (a peak amp).}$$

The factor used to describe the normalized band width is the quality factor, Q, where

$$\frac{1}{Q} = \frac{\omega_2 - \omega_1}{\omega_n}$$

In conjunction with the Q factor one can compare the AF (amplification factor) for different materials. One significant constraint is that the geometry of the

specimen and system remain the same, i.e. the measurement is unique to the particular setup.

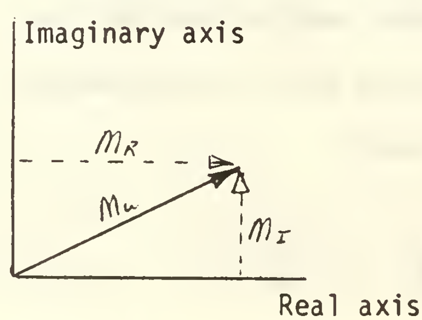
4. The Complex Modulus, the Dynamic Modulus, and the Tangent of the Phase Shift, i.e., Loss Factor.

These three measures are interrelated and can be used to describe more completely the behavior of high damping materials. The modulus of elasticity in a high damping material can be expressed in a complex form, as

$$M = M_R(1 + ig), \text{ where } gM_R^2 = M_I.$$

The tangent of the phase angle is related to the two components of the modulus by the equation

$$\tan \alpha = \frac{M_I}{M_R}$$



α, the phase angle is directly measurable as will be described. Also directly measurable is the dynamic modulus, M_W.

M_W, the dynamic modulus is the vector sum of the two moduli. It is the apparent modulus of the material and changes with frequency. Wasilewski[11] relates the use of commercially available equipment for this purpose.

If the phase angle α and the dynamic modulus can be obtained, then the complex modulus is completely described.

See Entwistle [12] for a more complete development including the Zener model.

Experimental Techniques

Techniques both used and proposed for the experimental determination of damping have been cataloged by Bert[7]. They are as follows:

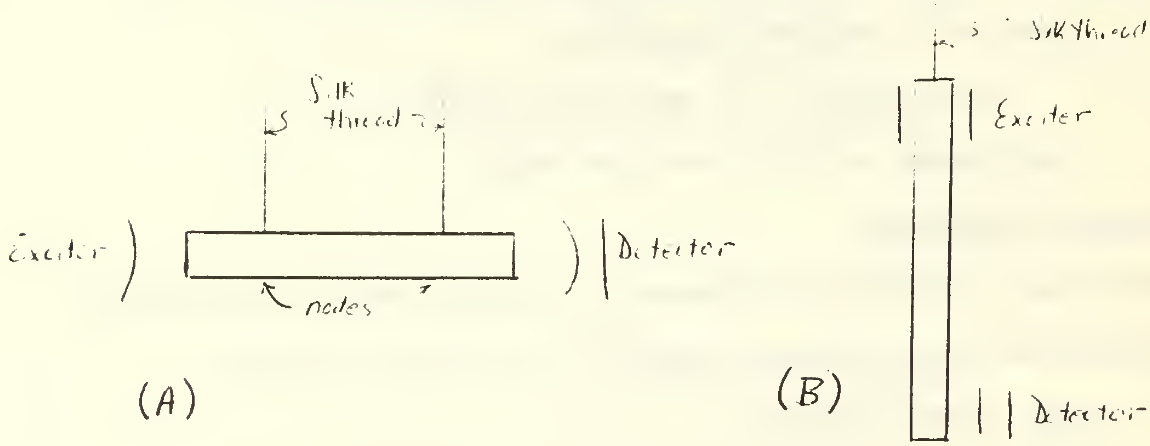
1. Decay of free vibration
   - (a) axial
   - (b) torsional
   - (c) bending moment
2. Resonant response
   - (a) bar in axial, torsional or bending motion
   - (b) plate or shell
   - (c) block or cube
3. Nonresonant forced vibration
4. Wave propagation
   - (a) continuous (steady state) wave
   - (b) pulsed wave

5. Rotating beam

(Adaptation of flexure vibration)

A proposed experimental system for high-damping materials would ideally include the determination of the dynamic modulus and phase angle. The experimental technique might make use of methods in Groups 2 and 3 in the above listing.

In resonant frequency response the specimen may be suspended from its nodal points, horizontally, or if nonresonant response is anticipated, the specimen should be suspended from its forced end vertically.



In Case B the detector could be moved vertically to adjust to the changing node pattern. The exciter and detector might typically be either magnetostrictive or electrostatic or a combination thereof. Magnetic materials tend to absorb energy from magnetostrictive devices. See Bert (7) and Entwistle (10) for a more complete discussion of this type of equipment.

Appendix B: Selected Bibliography on High-Damping Alloys

1. J. W. Jensen and D. F. Walsh, "Mn-Cu Damping Alloys", Bureau of Mines Bulletin 624, 1965.

2. E. J. Czyryca and M. G. Vassilavos, "Development of Improved Alloys for Navy Ships' Propellers: Phase I - High Damping Alloys", NSRDC Report 3236, June 1971.

3. J. A. Rowland, C. E. Armantrout, and D. F. Walsh, "Casting and Fabrication of High Damping Mn-Cu Alloys", Bureau of Mines Report 5127, 1955.

4. J. W. Jensen and A. E. Schwaneke, "Fatigue Properties of Mn-Cu Damping Alloys", Bureau of Mines Report 5853, 1961.

5. R. M. Lucas, "How to Select Materials for Noise Control", Mat. Eng. Dec. 1972, p. 60.

6. R. S. Dean, E. V. Potter, R. W. Huber, and H. C. Lukens, "The Damping Capacity of Cu-Mn Alloys", Trans. ASM 40 (1946) 355.

7. R. S. Dean, C. T. Anderson, and E. V. Potter, "The Alloys of Mn and Cu: Vibration Damping Capacity", Trans. ASM, June 1941, p. 402.

8. J. M. Langham, "A New High Damping Alloy", presented at 17th Annual Pacific Conference of the American Foundryman's Society; Stone Manganese Marine Technical Paper No. 6, April 1968; Foundry Trade Journal, June 6, 1966, p. 989.

9. D. Birchon, "Hidamets, Metals to Reduce Noise and Vibration", The Engineer, Aug. 5, 1966, p. 207.

10. A. V. Siefert and F. T. Worrell", The Role of Tetragonal Twins in the Internal Friction of Cu-Mn Alloys", J. App.Phys. 22 (1951) 1257.

11. Z. S. Basinski and J. W. Christian, "The Cubic-Tetragonal Transformation in Mn-Cu Alloys", J. Inst. Metals 80 (1951-52) 659.

12. J. W. Jensen and J. A. Rowland, Jr., "Mn-Cu High Damping Alloys", Product Engineering, May 1956, p. 135.

13. D. Birchon, "High Damping Alloys", Eng. Mat. and Design, Sept 1964, p. 606, Oct. 1964, p. 692.

14. D. W. James, "High Damping Metals for Engineering Applications", Mat. Sci. and Eng. 4 (1969) 1.

Appendix C: Names and Addresses of "Quiet Metal" Alloy Suppliers and Sources of Information

1. International Copper Research Association, Inc.
   825 Third Avenue, New York, New York 10022
   (212) 421-9090
   Attn: Dr. L. McDonald Schetky, Technical Director, Metallurgy
   (Development and marketing of "Incramute")

2. Olin Corporation
   Metals Research Laboratories
   91 Shelton Avenue
   New Haven, Connecticut 06504
   (203) 777-7911
   Attn: Dr. J. Winter, Associate Director, Physical Metallurgy
   (Producers of "Incramute")

3. Stone Manganese Marine, Limited
   Riverside House, Anchor and Hope Lane
   London SE7 7SZ, ENGLAND
   01-858-6171 (Telex: 897359)
   Attn: A. Tuffrey, Chief Research Metallurgist
   (Supplier of "Sonoston")

4. TIMET
   Toronto Technical Lab
   Toronto, Ohio 43964
   (614) 537-1571
   Attn: Mr. Joe Patric/Mr. Jim Partridge
   (Supplier of "Nitinol")

5. Mr. W. J. Buehler
   Magnetism and Metallurgy Division
   Naval Ordnance Laboratory
   White Oak
   Silver Spring, Maryland 20910
   (Information on applicability of "Nitinols")

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